Abstract

Climate change could aggravate periodic and chronic shortfalls of water, particularly in arid and semi-arid areas of the world (IPCC, 2001). Climate change is likely to accelerate the global hydrological cycle, with increase in temperature, changes in precipitation patterns, and evapotranspiration affecting the water quantity and quality, water availability and demands. The various components of a surface water resources system affected by climate change may include the water availability, irrigation demands, water quality, hydropower generation, ground water recharge, soil moisture etc. It is prudent to examine the anticipated impacts of climate change on these different components individually or combinedly with a view to developing responses to minimize the climate change induced risk in water resources systems. Assessment of climate change impacts on water resources essentially involves downscaling the projections of climatic variables (e.g., temperature, humidity, mean sea level pressure etc.) to hydrologic variables (e.g., precipitation and streamflow), at regional scale. Statistical downscaling methods are generally used in the hydrological impact assessment studies for downscaling climate projections provided by the General Circulation Models (GCMs). GCMs are climate models designed to simulate time series of climate variables globally, accounting for the greenhouse gases in the atmosphere. The statistical techniques used to bridge the spatial and temporal resolution gaps between what GCMs are currently able to provide and what impact assessment studies require are called as statistical downscaling methods. Generally, these methods involve deriving empirical relationships that transform large-scale simulations of climate variables (referred as the predictors) provided by a GCM to regional scale hydrologic variables (referred as the predictands). This general methodology is characterized by various uncertainties such as GCM and scenario uncertainty, uncertainty due to initial conditions of the GCMs, uncertainty due to downscaling methods, uncertainty due to hydrological model used for impact assessment and uncertainty resulting from multiple stake holders in a water resources system.

The research reported in this thesis contributes towards (i) development of methodologies for climate change impact assessment of various components of a water resources system, such as water quality, water availability, irrigation and reservoir operation, and (ii) quantification of GCM and scenario uncertainties in hydrologic impacts of climate change. Further, an integrated reservoir operation model is developed to derive optimal operating policies under the projected scenarios of water availability, irrigation water demands, and water quality due to climate change accounting for various sources of uncertainties. Hydropower generation is also one of the objectives in the reservoir operation.

The possible climate change impact on river water quality is initially analyzed with respect to hypothetical scenarios of temperature and streamflow, which are affected by changes in precipitation and air temperature respectively. These possible hypothetical scenarios are constructed for the streamflow and river water temperature based on recent changes in the observed data. The water quality response is simulated, both for the present conditions and for conditions resulting from the hypothetical scenarios, using the water quality simulation model, QUAL2K. A Fuzzy Waste Load Allocation Model

(FWLAM) is used as a river water quality management model to derive optimal treatment levels for the dischargers in response to the hypothetical scenarios of streamflow and water temperature. The scenarios considered for possible changes in air temperature (+1 ^{o}C and +2 ^{o}C) and streamflow (-0%, -10%, -20%) resulted in a substantial decrease in the Dissolved Oxygen (DO) levels, increase in Biochemical Oxygen Demand (BOD) and river water temperature for the case study of the Tunga-Bhadra River, India. The river water quality indicators are analyzed for the hypothetical scenarios when the BOD of the effluent discharges is at safe permissible level set by Pollution Control Boards (PCBs). A significant impairment in the water quality is observed for the case study, under the hypothetical scenarios considered.

A multi-variable statistical downscaling model based on Canonical Correlation Analysis (CCA) is then developed to downscale future projections of hydro-meteorological variables to be used in the impact assessment study of river water quality. The CCA downscaling model is used to relate the surface-based observations and atmospheric variables to obtain the simultaneous projection of hydro-meteorological variables. Statistical relationships in terms of canonical regression equations are obtained for each of the hydro-meteorological predictands using the reanalysis data and surface observations. The reanalysis data provided by National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) are used for the purpose. The regression equations are applied to the simulated GCM output to model future projections of hydro-meteorological predictands. An advantage of the CCA methodology in the context of downscaling is that the relationships between climate variables and the surface hydrologic variables are simultaneously expressed, by retaining the explained variance between the two sets. The CCA method is used to model the monthly hydro-meteorological variables in the Tunga-Bhadra river basin for water quality impact assessment study.

A modeling framework of risk assessment is developed to integrate the hydro-meteorological projections downscaled from CCA model with a river water quality management model to quantify the future expected risk of low water quality under climate change. A Multiple Logistic Regression (MLR) is used to quantify the risk of Low Water Quality (LWQ) corresponding to a threshold DO level, by considering the streamflow and water temperature as explanatory variables. An Imprecise Fuzzy Waste Load Allocation Model (IFWLAM) is adopted to evaluate the future fractional removal policies for each of the dischargers by including the predicted future risk levels. The hydro-meteorological projections of streamflow, air temperature, relative humidity and wind speed are modeled using MIROC 3.2 GCM simulations with A1B scenario. The river water temperature is modeled by using an analytical temperature model that includes the downscaled hydro-meteorological variables. The river water temperature is projected to increase under climate change, for the scenario considered. The IFWLAM uses the downscaled projections of streamflow, simulated river water temperature and the predicted lower and upper future risk levels to determine the fraction removal policies for each of the dischargers. The results indicate that the optimal fractional removal levels required for the future scenarios will be higher compared to the present levels, even if the effluent loadings remain unchanged.

Climate change is likely to impact the agricultural sector directly with changes in rainfall and evapotranspiration. The regional climate change impacts on irrigation water demands are studied by quantifying the crop water demands for the possible changes of rainfall and evapotranspiration. The future projections of various meteorological variables affecting the irrigation demand are downscaled using CCA downscaling model with MIROC 3.2 GCM output for the A1B scenario. The future evapotranspiration is obtained using the Penman-Monteith evapotranspiration model accounting for the projected changes in temperature, relative humidity, solar radiation and wind speed. The monthly irrigation water demands of paddy, sugarcane, permanent garden and semidry crops quantified at nine downscaling locations covering the entire command area of the Bhadra river basin, used as a case study, are projected to increase for the future scenarios of 2020-2044, 2045-2069 and 2070-2095 under the climate change scenario considered.

The GCM and scenario uncertainty is modeled combinedly by deriving a multimodel weighted mean by assigning weights to each GCM and scenario. An entropy objective weighting scheme is proposed which exploits the information contained in various GCMs and scenarios in simulating the current and future climatology. Three GCMs, viz., CGCM2 (Meteorological Research Institute, Japan), MIROC3.2 medium resolution (Center for Climate System Research, Japan), and GISS model E20/Russell (NASA Goddard Institute for Space Studies, USA) with three scenarios A1B, A2 and B1 are used for obtaining the hydro-meteorological projections for the Bhadra river basin. Entropy weights are assigned to each GCM and scenario based on the performance of the GCM and scenario in reproducing the present climatology and deviation of each from the projected ensemble average. The proposed entropy weighting method is applied to projections of the hydro-meteorological variables obtained based on CCA downscaling method from outputs of the three GCMs and the three scenarios. The multimodel weighted mean projections are obtained for the future time slice of 2020-2060. Such weighted mean hydro-meteorological projections may be further used into the impact assessment model to address the climate model uncertainty in the water resources systems.

An integrated reservoir operation model is developed considering the objectives of irrigation, hydropower and downstream water quality under uncertainty due to climate change, uncertainty introduced by fuzziness in the goals of stakeholders and uncertainty due to the random nature of streamflow. The climate model uncertainty originating from the mismatch between projections from various GCMs under different scenarios is considered as first level of uncertainty, which is modeled by using the weighted mean hydro-meteorological projections. The second level of uncertainty considered is due to the imprecision and conflicting goals of the reservoir users, which is modeled by using fuzzy set theory. A Water Quantity Control Model (WQCM) is developed with fuzzy goals of the reservoir users to obtain water allocations among the different users of the reservoir corresponding to the projected demands. The water allocation model is updated to account for the projected demands in terms of revised fuzzy membership functions under climate change to develop optimal policies of the reservoir for future scenarios. The third level of uncertainty arises from the inherent variability of the reservoir inflow leading to uncertainty due to randomness, which is modeled by considering the reservoir inflow as a stochastic variable. The optimal monthly operating polices are derived using Stochastic Dynamic Programming (SDP), separately for the current and for the future periods of 2020-2040 and 2040-2060 The performance measures for Bhadra reservoir in terms of reliability and deficit ratios for each reservoir user (irrigation, hydropower and downstream water quality) are estimated with optimal SDP policy derived for current and future periods. The reliability with respect to irrigation, downstream water quality and hydropower show a decrease for 2020-2040 and 2040-2060, while deficit ratio increases for these periods. The results reveal that climate change is likely to affect the reservoir performance significantly and changes in the reservoir operation for the future scenarios is unable to restore the past performance levels. Hence, development of adaptive responses to mitigate the effects of climate change is vital to improve the overall reservoir performance.